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EFFECTS OF BASE BLEED AND SUPERSONIC NOZZLE INJECTION ON BASE PRESSURE

Lyle D. Kayser

March 1975

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Base Bleed

20. ABSTRACT (Continue on reverse side if necessary and identify by block number) (ds/lca)

Base pressure tests were conducted on an ogive-cylinder configuration at Mach numbers 2.5, 3.0 and 3.5. Measurements were obtained while bleeding air into the base region through a variety of base-bleed configurations. For two of the configurations, air was injected into the base through a supersonic sustainer type nozzle simultaneously with base bleed injection. The mass flow rates through the sustainer nozzle and base bleed openings were varied
(Continued)

20. ABSTRACT (Continued)

at each Mach number. The results show a net decrease in base drag due to base bleed and a net increase due to supersonic injection whether or not the bleed air and the supersonic air are introduced simultaneously.

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I. INTRODUCTION

The effects of fluid injection into the base region of a missile or projectile are of interest to the Army. It is well known that injection of a fluid can decrease base drag and increase the vehicle range. In some missile systems, it may be necessary to bleed off excess gases; such injectants should be introduced into the base region in a manner which will provide the best overall flight characteristics.

The tests discussed in this report were conducted for the Army Missile Command, Redstone Arsenal, Alabama. These tests were conducted in April 1970 and were a part of a series of experimental and theoretical base flow studies with emphasis on fluid injection into the base region. Because of renewed Army interest in reduction of base drag through fluid injection, these data have been reviewed and are now being published in this report.

In this test program, base pressure measurements were obtained at supersonic speeds with base injection. Different base bleed configurations were tested with and without simultaneous operation of a supersonic sustainer nozzle. Mass flow rates of both the bleed air and sustainer air were varied.

II. APPARATUS

A. Wind Tunnel

The tests were conducted in the Ballistic Research Laboratories' Supersonic Wind Tunnel No. 1. Tunnel No. 1 is of the continuous flow, closed circuit, variable density type and has a flexible nozzle for obtaining Mach numbers from 1.5 to 5.0. The test section size is 13 inches wide by 15 inches high (33.0 by 38.1 centimetres) and is shown in Figure 1 with the model installed.

B. Model

The model was a tangent-ogive cylinder 2.5 inches (6.35 centimetres) in diameter, six calibers long and was supported by the strut which was attached to the tunnel ceiling (again see Figure 1). Figure 2 is a sketch of the model along with significant dimensions. Base bleed air and sustainer nozzle air were supplied through passages in the supporting strut. The sustainer nozzle geometry is also shown in Figure 2 and is a supersonic type nozzle with an exit Mach number of 2.71. The six base bleed configurations and base pressure tap locations are shown in Figure 3. The base bleed openings might be classified as the flat-plate-orifice type.

C. Auxiliary Air

Air to the sustainer nozzle was supplied from Compressor Plant No. 2 which is designed to supply high pressure air to the Hypersonic Tunnel. When operating Tunnel No. 1 (supersonic tunnel), Plant No. 2 can be utilized as an auxiliary air supply. Air from Plant No. 2 can be supplied to Tunnel No. 1 at pressures greater than 300 psia (2068 kPa) utilizing two of the three available compressor units.

Base bleed air was supplied from the air storage sphere which is normally used to replenish dry air to the wind tunnel circuits. Pressure in the sphere is typically maintained at 70 to 90 psia (483 to 621 kPa). Base bleed air could have been supplied from Plant No. 2, but separate sources were used because part of the test program required base bleed only; for this reason, operation of Plant No. 2 was not required during these periods.

D. Instrumentation

Approximate locations of model base pressure orifices are shown in Figure 3. Total and static pressures were measured in the base-bleed chamber and total pressure was measured in the sustainer supply chamber (see Figure 2). Pressure orifices were connected to stainless steel tubing of 0.058 inch (0.147 centimetre) o.d. by 0.008 inch (0.020 centimetre) wall which was routed through the supporting strut leading edge cowling; the stainless tubing was then connected to 0.062 inch (0.157 centimetre) i.d. copper tubing which was routed to the pressure scanner. Pressures were measured with Stathum absolute pressure transducers which are linear to within ± 0.25 percent of the full scale range. The pressure scanner can utilize seven transducers and each transducer can be opened to four ports giving a total capacity for measuring 28 pressures. Tunnel supply pressure and the sustainer nozzle supply pressure were measured with separate transducers because the scanner is limited to a maximum pressure of 25 psia (172 kPa).

Electrical signals from the transducers were converted to digital readings by an automatic data readout system. Data were tabulated with a Flexowriter and punched on paper tape for computer processing.

The sustainer nozzle throat was utilized as a metering device for measuring the mass flow rate through the sustainer. The base bleed mass flow rate was measured by placing a metering venturi in the supply line outside of the tunnel. Venturies with throat diameters of 0.140, 0.200, 0.350, and 0.500 inch (0.356, 0.508, 0.889, and 1.27 centimetres) were available but only the two smaller venturies were used. Total pressure and temperature upstream from the throat and static pressure at the throat were measured. A Honeywell direct measuring recorder was used for measuring the base bleed and sustainer air temperatures.

III. PROCEDURES

A. Test Procedure

Tunnel supply pressure and temperature were set at the desired conditions. The sustainer nozzle supply pressure was then adjusted to the required level by monitoring the automatic readout dial indicators; this pressure was then retained at a constant value while the base bleed air supply pressure was set at different levels. The base bleed pressure was set by monitoring the output for the outer probe of the base bleed chamber total pressure rake (see Figure 2). At each combination of pressure settings, all pressures and temperatures were recorded. Data were obtained at Mach numbers 2.5, 3.0, 3.5 with corresponding Reynolds numbers of 7.1×10^6, 7.8×10^6, and 8.0×10^6 based on model length. All data were obtained with the model attitude at zero degrees.

Total pressures upstream from the base-bleed mass-flow measuring orifice and throat static pressures were monitored to insure that sonic flow was maintained in the throat at all times. It was necessary to maintain sonic flow so that the mass flow rates could be determined with reasonable accuracy. If the flow at the throat was subsonic for a desired test condition, a smaller venturi was installed in the supply line, or if the flow was sonic but the desired mass flow rate could not be attained, a larger venturi was then installed.

B. Data Reduction Procedure

A precision resistor is permanently attached to the pressure transducer electronics package which can easily be shunted across one leg of the transducer strain-gage bridge. The resistance change caused by the shunt is equivalent to that caused by a specific pressure change which is determined during a bench calibration. During a test, the only calibration needed is a data system readout with the transducer shunted. Transducer output is assumed to be linear, hence the raw data reading is merely multiplied by a constant to obtain the pressure. Air supply temperatures were measured using iron-constantan thermocouples and a Honeywell-Brown direct temperature measuring instrument.

Bench tests were not conducted to determine the nozzle discharge coefficient or the discharge coefficients for the metering Venturies. Handbook values (reference 1) for smooth nozzles indicate that discharge coefficients are typically 0.98 and may be as large as 0.995. Mass flow rates for these tests were computed using the continuity equation for sonic flow at the throat and assuming the discharge coefficient to be 0.98.

---

1. *Mechanical Engineers Handbook by Lionel S. Marks, McGraw-Hill Book Co., Inc., 5th Edition, New York, (1951).*

Data Accuracy: Pressure transducers are linear to within ± 0.25% of the full scale output. Since pressures are usually less than full scale and small random instrumentation errors exist, it is estimated that typical accuracy of pressure measurements is ± 1.0%. Accuracy of temperature measurements is estimated to be of the same order as the pressure measurements.

Accuracy of the mass flow calculation is dependent on the accuracy of the temperature, pressure and discharge coefficient. A discharge coefficient accuracy of ± 2.0 percent would seem to be a reasonable estimate, hence the overall accuracy of mass flow rates should be within ± 4.0 percent.

IV. DISCUSSION

Variation of pressure across the base of the model was reasonably constant for most flow situations. Figure 4 shows some of the larger variations observed during the test program; the higher mass flow rates of base bleed seemed to cause the greater variations. The mean value of base pressure was not computed but the pressure at $r/r_b = 0.93$ was typically average and hence this pressure was used in the plots of Figures 5 to 7.

Variation of base pressure with base bleed and no injection through the supersonic nozzle is shown in Figure 5a. The peak pressure for each of the configurations increases with the area of the base bleed opening. Insufficient data were available to determine the Mach number or velocity through the base bleed openings but approximate calculations show that at the peak pressure, the Mach number of the flow at exit was typically greater than 0.5. This relatively high velocity indicates that the base bleed air has sufficient momentum to start lowering the base pressure through ejector type action. Figure 5 also suggests that for small amounts of base bleed up to approximately $\dot{m}_{bb}/\dot{m}_\infty \cong 0.004$, the base pressure is independent of the base configuration. Figures 5b and 5c are results similar to those of Figure 5a but show the effect of Mach number on base pressure.

Figure 6 shows the effect of injection through the supersonic nozzle on base pressure. Comparison of the results for configurations 2 and 6 shows that the geometry of base bleed opening does not have any noticeable effect on base pressure provided there is no base bleed injectant. The initial rise in base pressure is believed similar to that caused by the base bleed because the supply pressure was not high enough to give supersonic flow; as the supply pressure increased, flow became supersonic and the ejector type action caused a sharp decrease in the base pressure. As the supply pressure is increased further the base pressure begins a gradual rise; this pressure rise is believed caused by the jet plume resulting from an underexpanded flow at the nozzle exit. With a high supply pressure, flow at the nozzle exit may be sufficiently underexpanded that the resulting plume may cause separation of the boundary layer upstream from the trailing edge corner. Boundary layer separation was not observed in these tests but the shadowgraph of Figure 8 shows a plume of sufficient size to affect the boundary layer on a smaller base diameter such as a boattailed configuration.

Figures 7a-f show the combined effects of base bleed and supersonic nozzle injection; if the effects of these two modes of injection were independent, the curves would be parallel. The curves of Figures 7a-f are not parallel but do show to some degree a parallel character indicating to what extent the modes of injection affect the base pressure independently.

No theoretical comparisons were made with the data but it is worth noting that extensive work has been supported by the Army Missile Command in the area of axisymmetric base pressure in a supersonic free stream with propulsive nozzle flows. A computer program for computing base pressure for the conditions stated above was developed; results of this work may be found in references 2, 3, and 4.

The trends of the experimental data are as one expects; that is, low momentum injection (base bleed) increases the base pressure while high momentum injection decreases the base pressure. It is well known that base bleed type injection increases base pressure; that is to be expected because the net amount of gas injected at low momentum will

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2. *A. L. Addy, "Analysis of the Axisymmetric Base-Pressure and Base-Temperature Problem with Supersonic Interacting Freestream-Nozzle Flows Based on the Flow Model of Korst, et al., Part I: A Computer Program and Representative Results for Cylindrical Afterbodies," Report No. RD-TR-69-12, U. S. Army Missile Command, Redstone Arsenal, Alabama (July 1969). AD 861434.*

3. *A. L. Addy, "Analysis of the Axisymmetric Base-Pressure and Base-Temperature Problem with Supersonic Interacting Freestream-Nozzle Flows Based on the Flow Model of Korst, et al., Part II: A Comparison and Correlation with Experiment for Cylindrical Afterbodies," Report No. RD-TR-69-13, U. S. Army Missile Command, Redstone Arsenal, Alabama (December 1969). AD 868895.*

4. *A. L. Addy, "Analysis of the Axisymmetric Base Pressure and Base-Temperature Problem with Supersonic Interacting Freestream-Nozzle Flows Based on the Flow Model of Korst, et al., Part III: A Computer Program and Representative Results for Cylindrical, Boattailed, or Flared Afterbodies," Report No. RD-TR-69-14, U. S. Army Missile Command, Redstone Arsenal, Alabama (February 1970). AD 875875.*

have to be accelerated sufficiently to negotiate the recompression. This acceleration will require a momentum exchange along the shear layer and a longer shear layer than for the case of no injection. A longer shear layer means a smaller turning angle, a higher base pressure and lower base drag. All air injected into the base region was at an ambient temperature of approximately 90° F (32° C) and no effects of heat addition were measured. Addition of heat in the recirculating region would increase the volume of the recirculating region, decrease the turning angle of the external flow and result in a higher base pressure. By the same reasoning, for a given mass rate of injection, a low molecular weight gas would give a greater volume increase and hence a higher base pressure than that for a high molecular weight gas.

Experimental results of reference 5 for hypersonic flow, laminar boundary layer and low momentum injection show that base pressure correlates with the parameter I.

$$I = \frac{\dot{m}_{bb}}{2\dot{m}_{B.L.}} \sqrt{\frac{M_{air}}{M_i}}$$

The ratio of base pressure with injectant to the base pressure without injectant varies nearly linearly with the above parameter I for pressure ratios up to about 1.25. This correlation shows that the base pressure increase is proportional to the rate of injected gas and inversely proportional to the square root of the molecular weight of injectant.

High momentum injection is expected to decrease the base pressure (see Figure 6) because this type of injection is analogous to that used in ejector systems which are used for obtaining low pressures or pumping fluids by the suction of a jet flow.

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5. *D. J. Collins, L. Lees, and A. Roshko, "Near Wake of a Hypersonic Blunt Body with Mass Addition,"* *AIAA Journal, Vol. 8, No. 5, May 1970, pp. 833-842.*

V. CONCLUDING REMARKS

The effectiveness of base bleed in reducing drag decreases with increasing mass flow; the base drag reaches a minimum for a given amount of base bleed and then increases with increasing mass flow rates provided the base configuration remains unchanged.

A greater reduction in base drag can be attained by increasing both the area of the bleed openings and the mass flow rate.

For moderate mass flow rates, supersonic injection lowers the base pressure and hence increases base drag.

The independent effects of base bleed and supersonic injection are qualitatively additive for simultaneous injection.

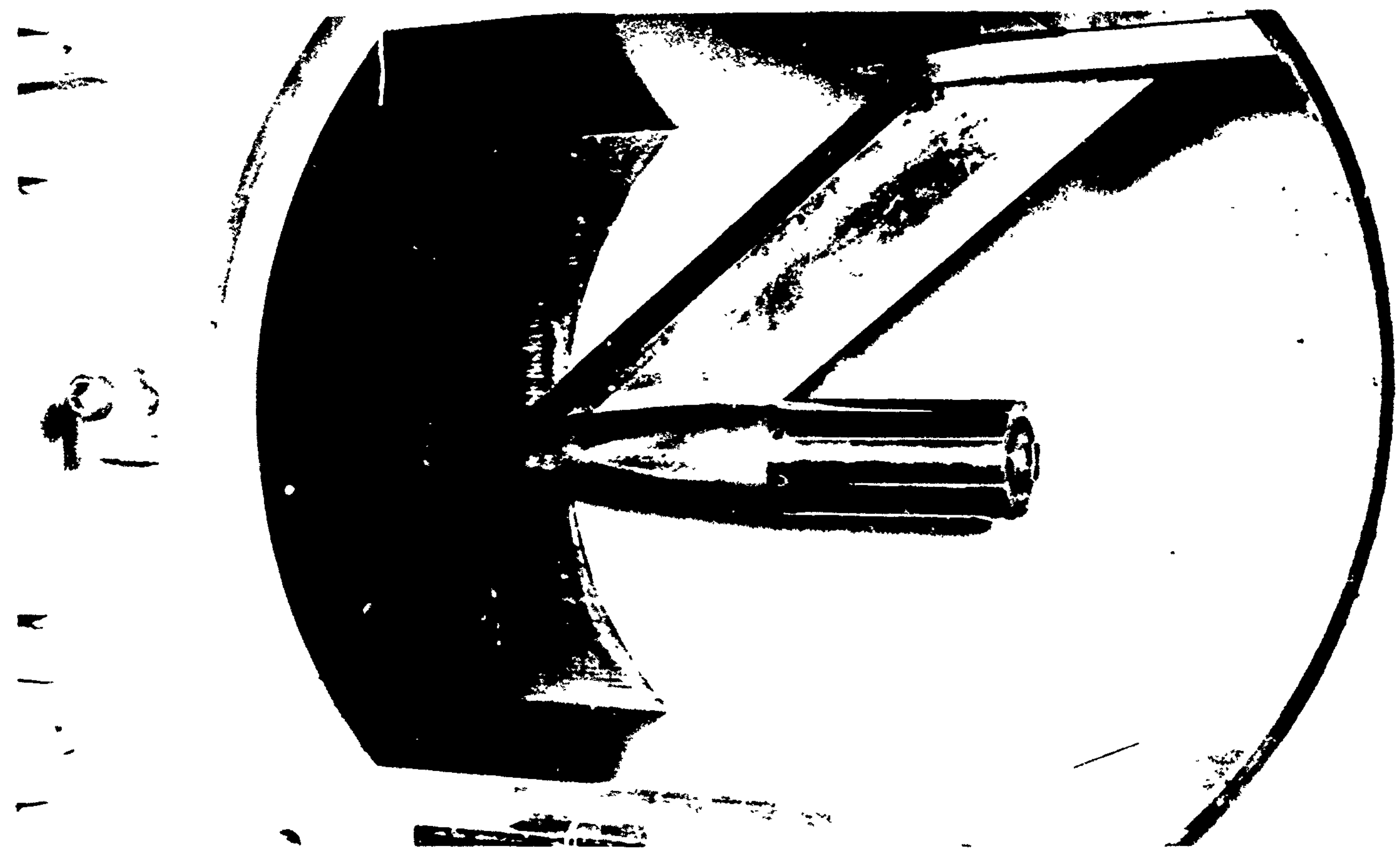

Figure 1. Model Installation Photograph

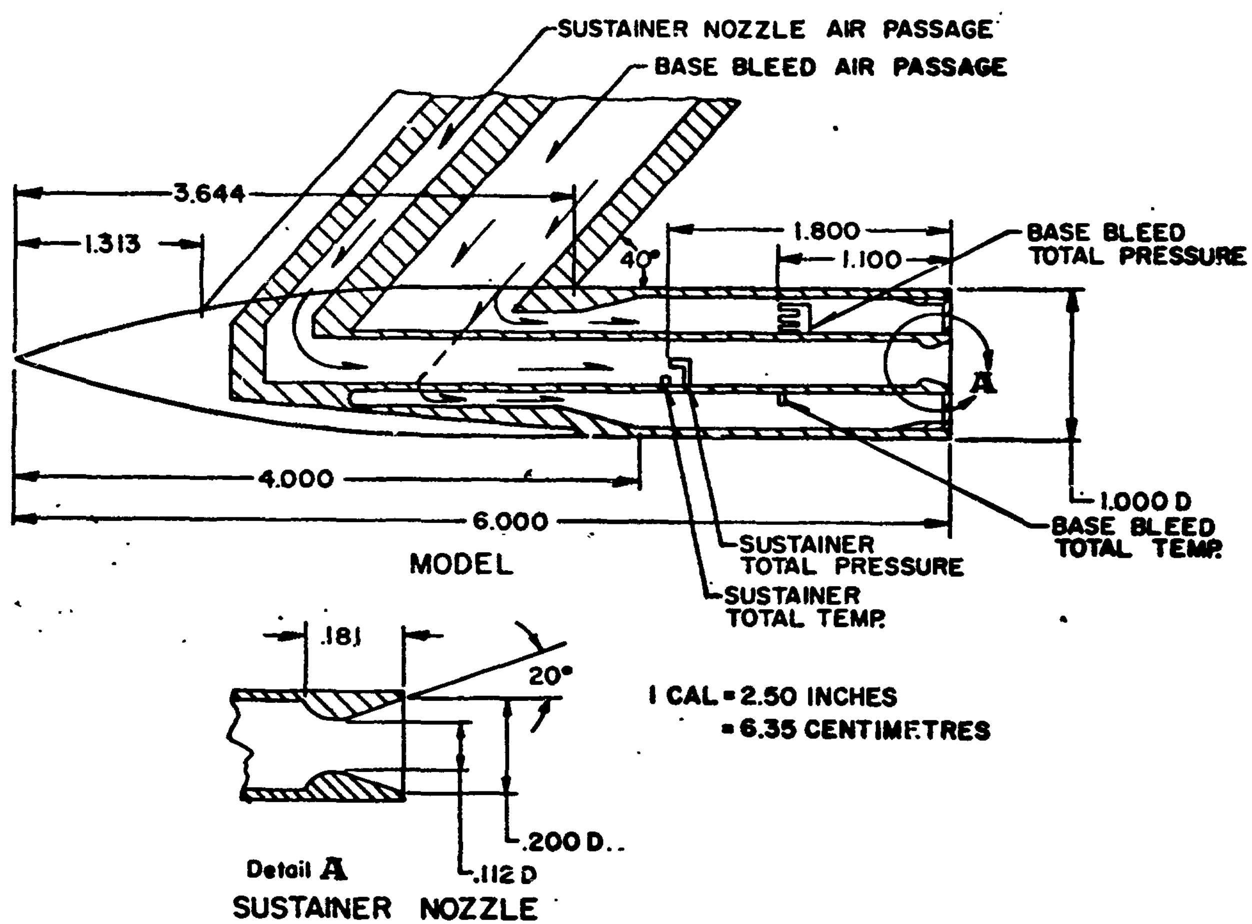

Figure 2. Model Geometry

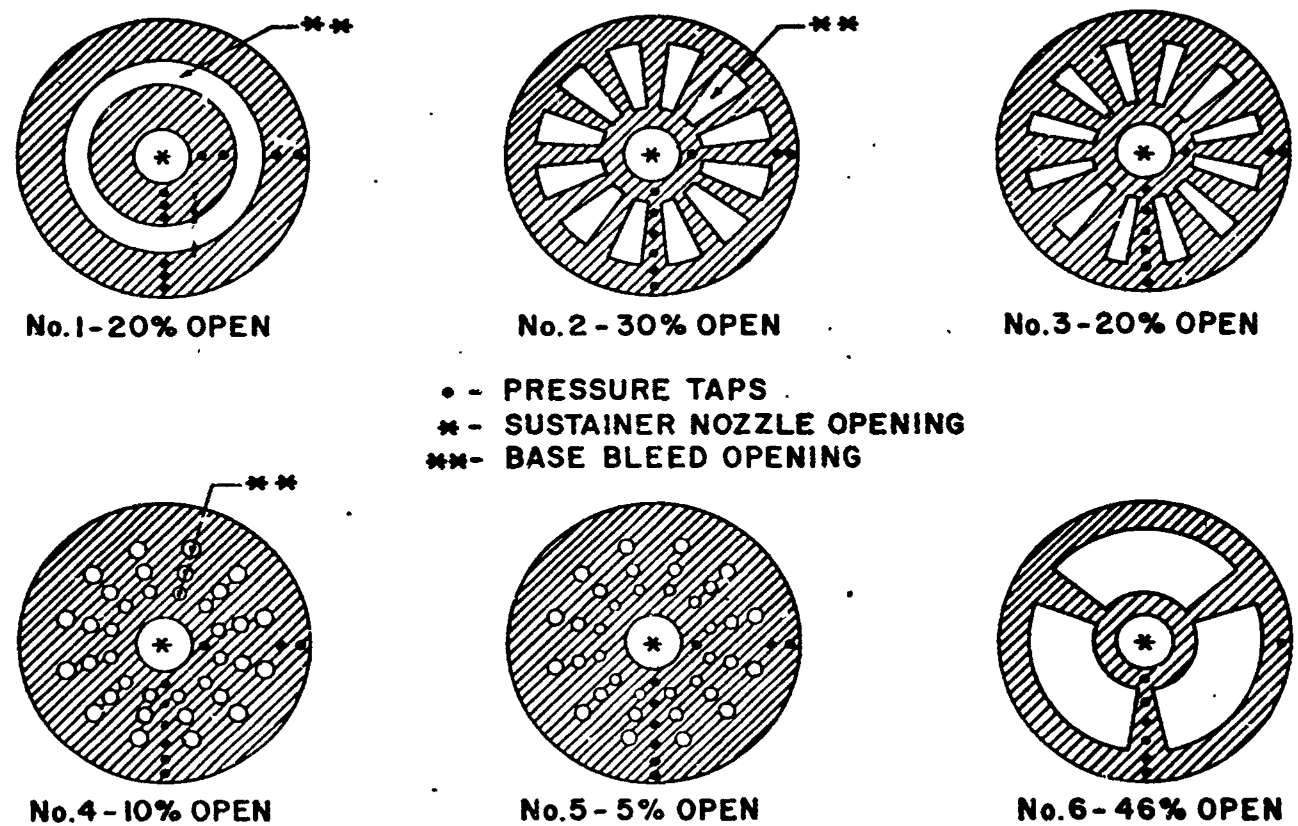

Figure 3. Model Base Configurations

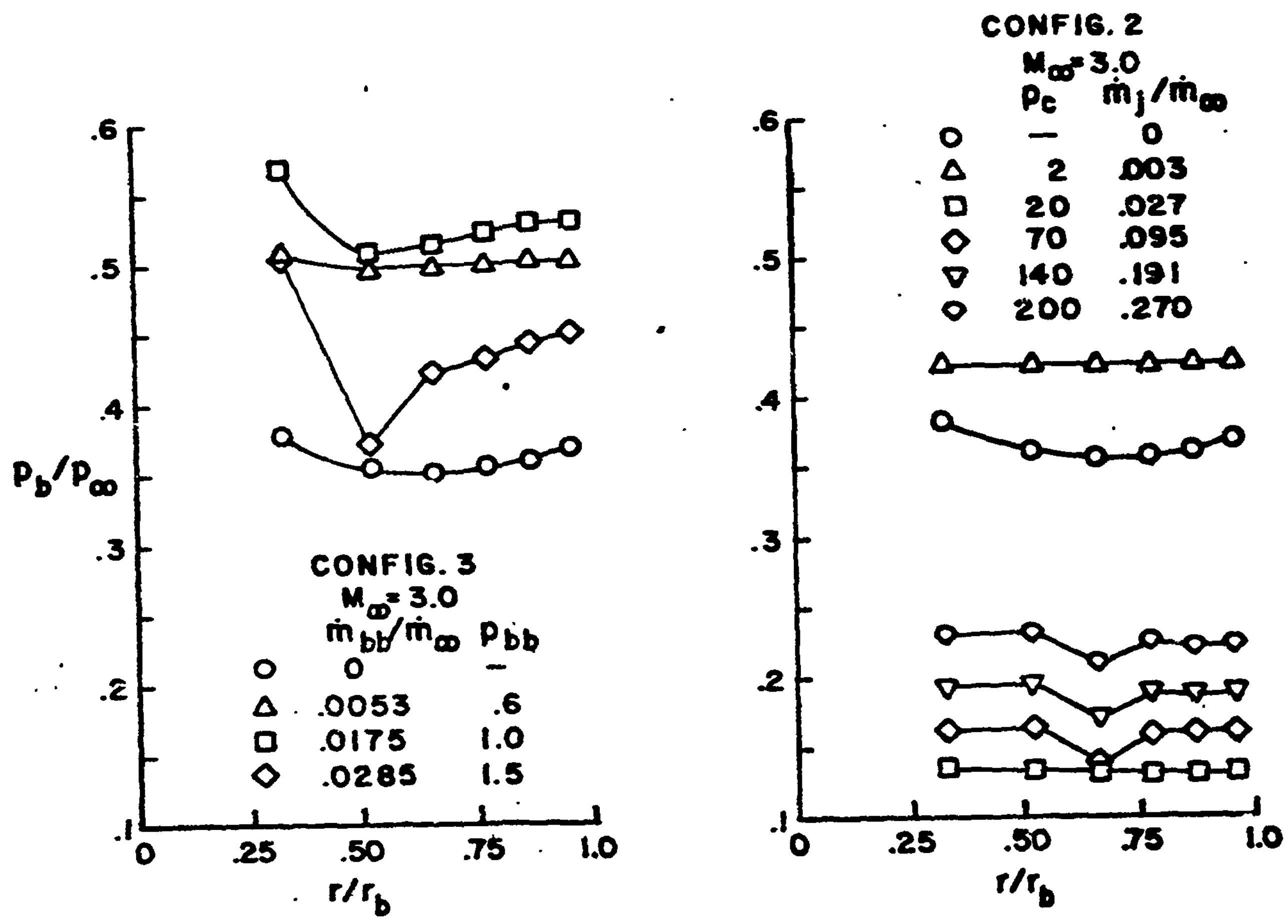

Figure 4. Radial Variation of Base Pressure

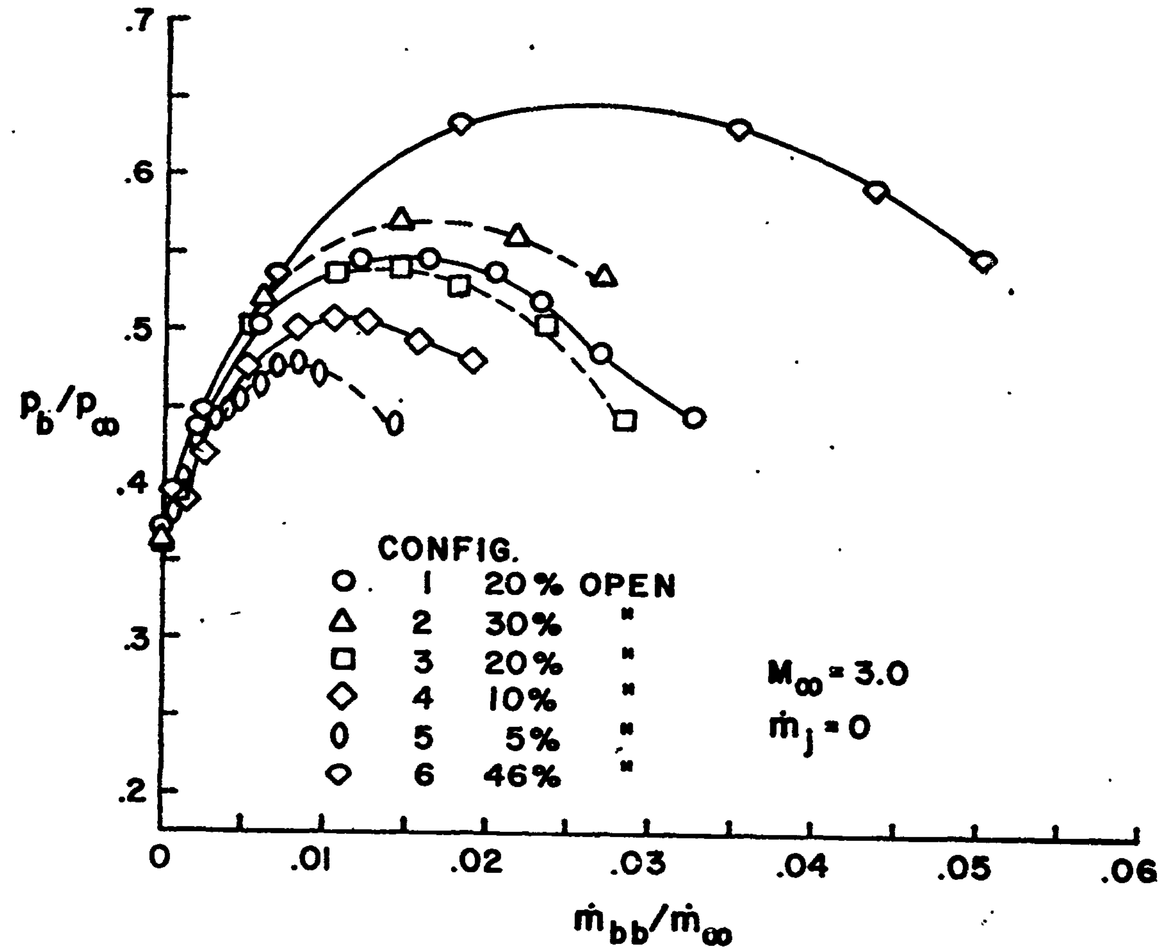

Figure 5. Base Bleed Effect on Base Pressure

a. $M_\infty = 3.0$, Configurations 1 through 6

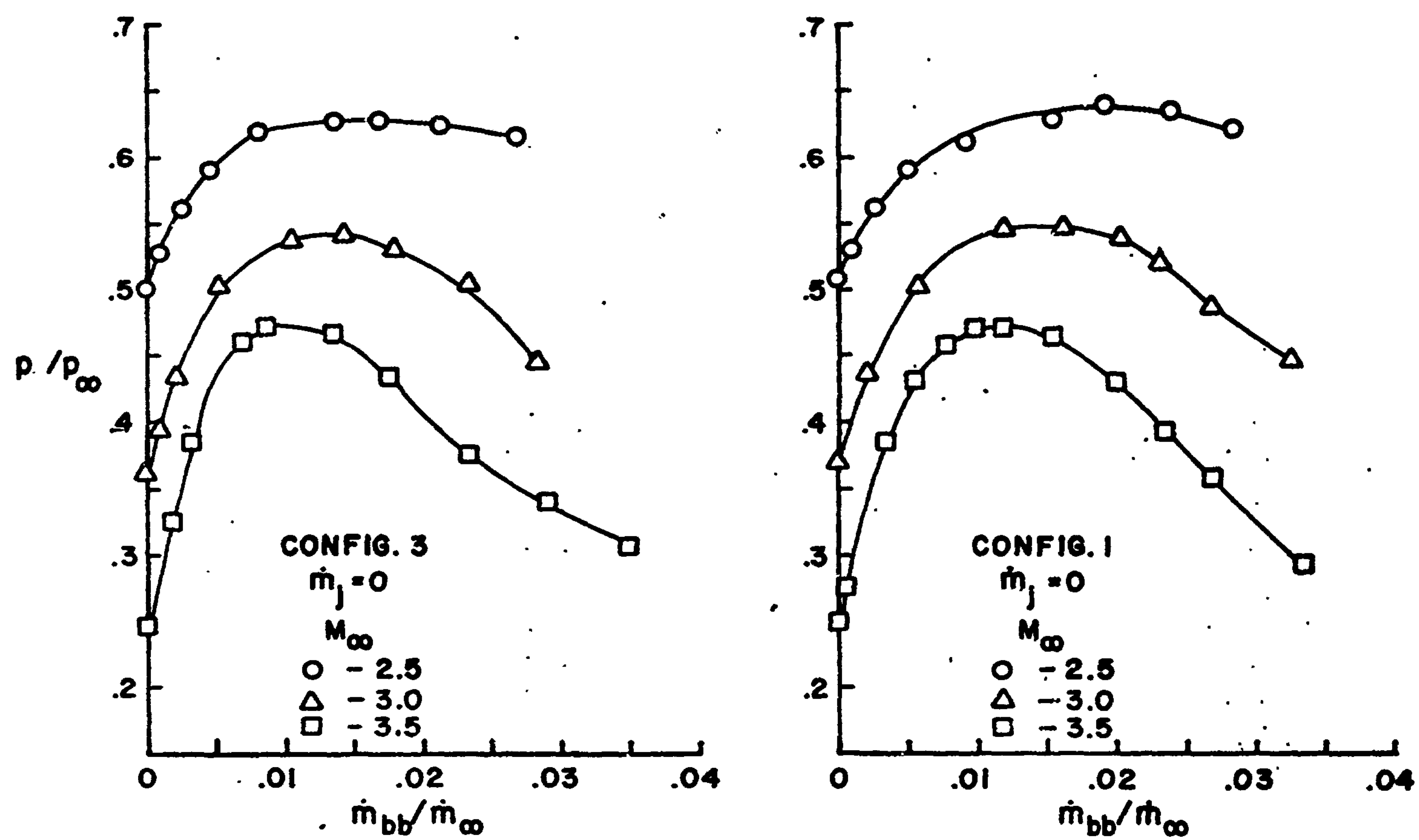

Figure 5. Continued

b. M_∞ = 2.5, 3.0, 3.5, Configurations 1 and 3

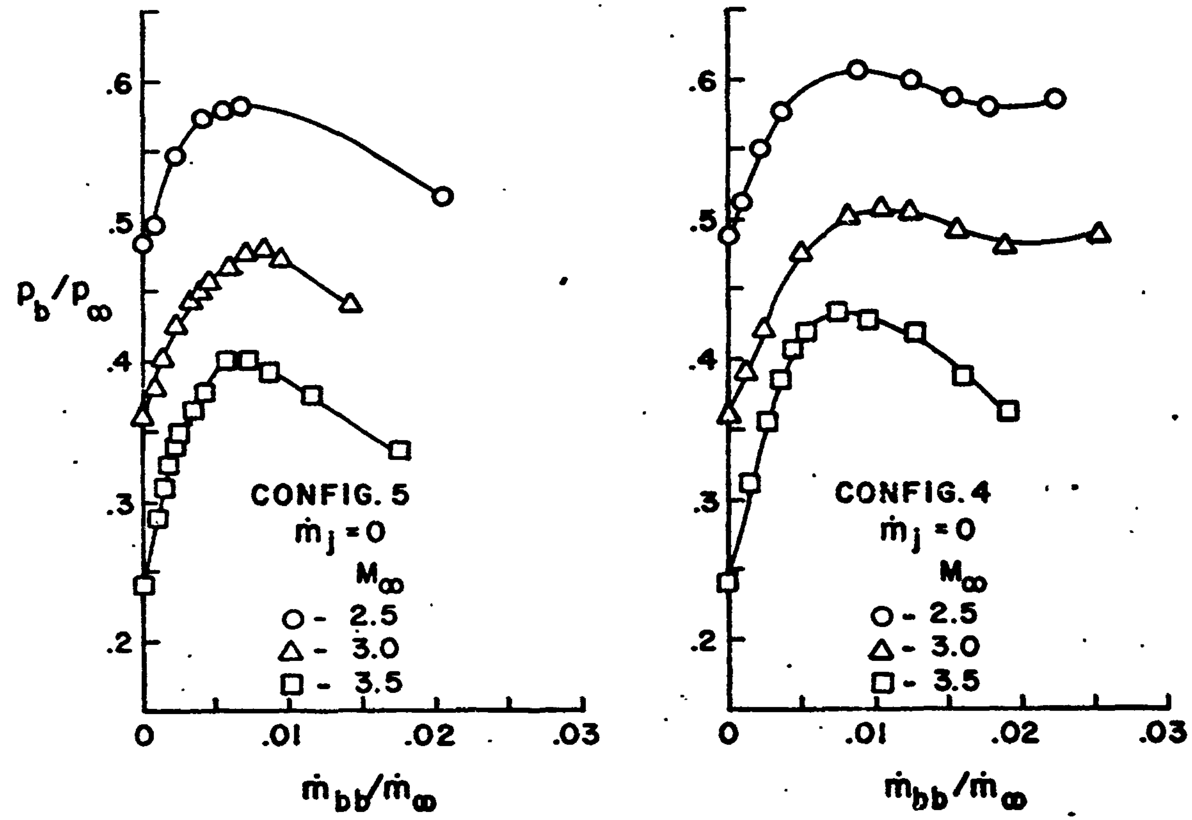

Figure 5. Concluded

c. M_∞ = 2.5, 3.0, 3.5, Configurations 4 and 5

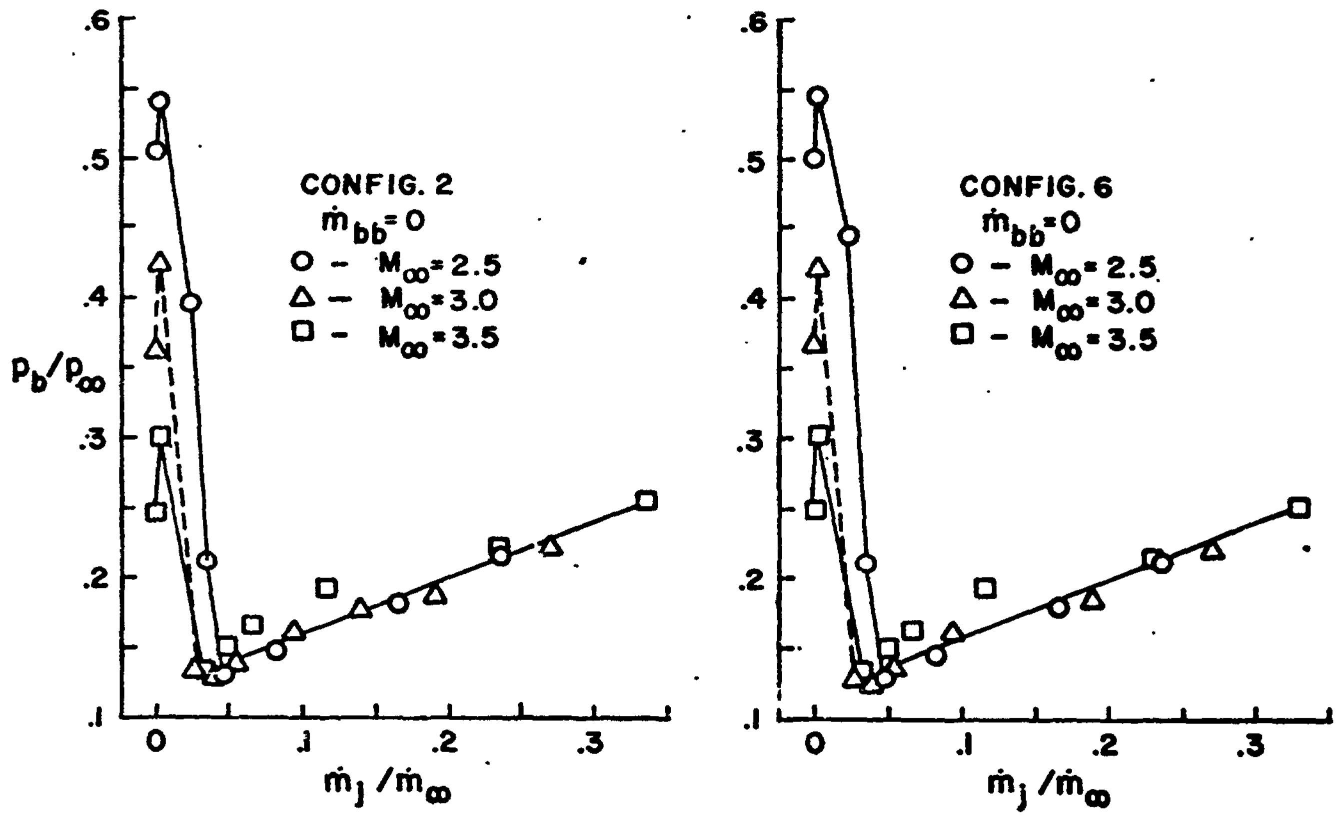

Figure 6. Supersonic Nozzle Injection Effect on Base Pressure

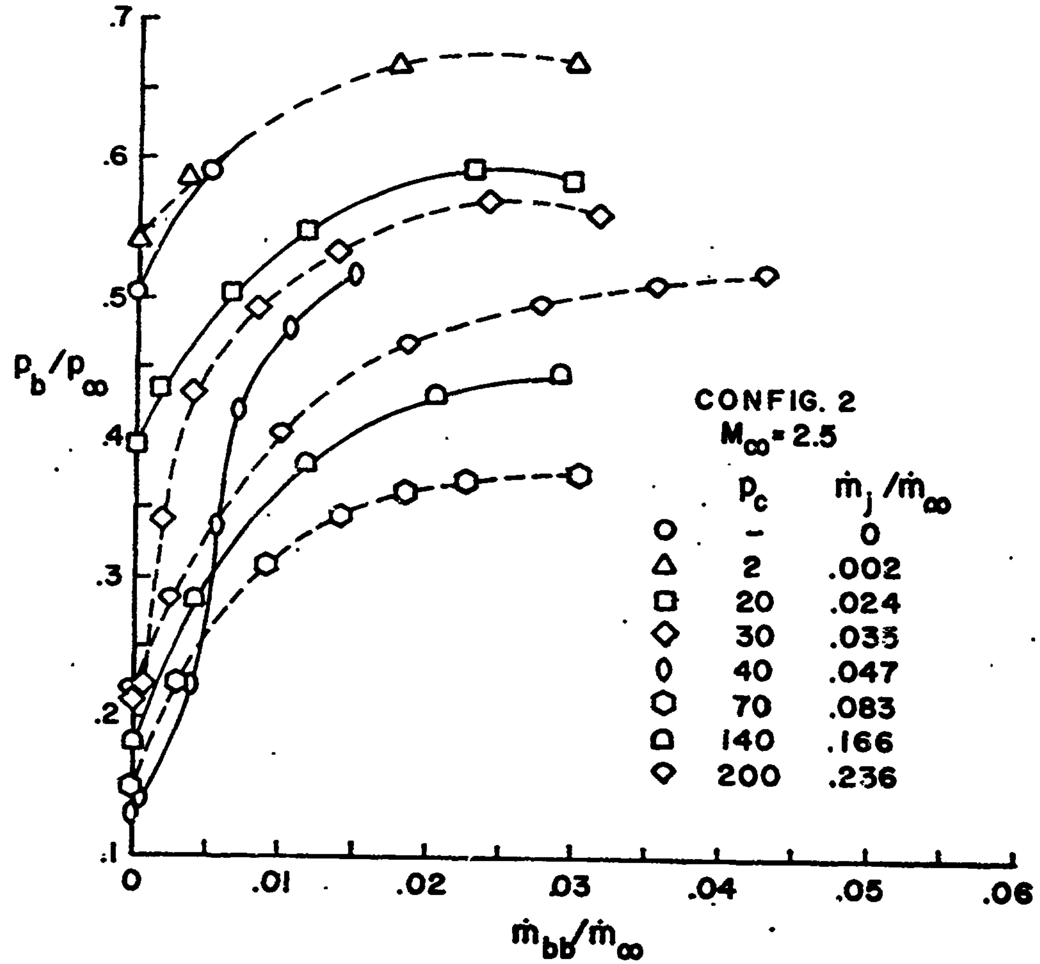

Figure 7. Combined Effects of Base Bleed and Supersonic Nozzle Injection

a. Configuration 2, $M_\infty = 2.5$

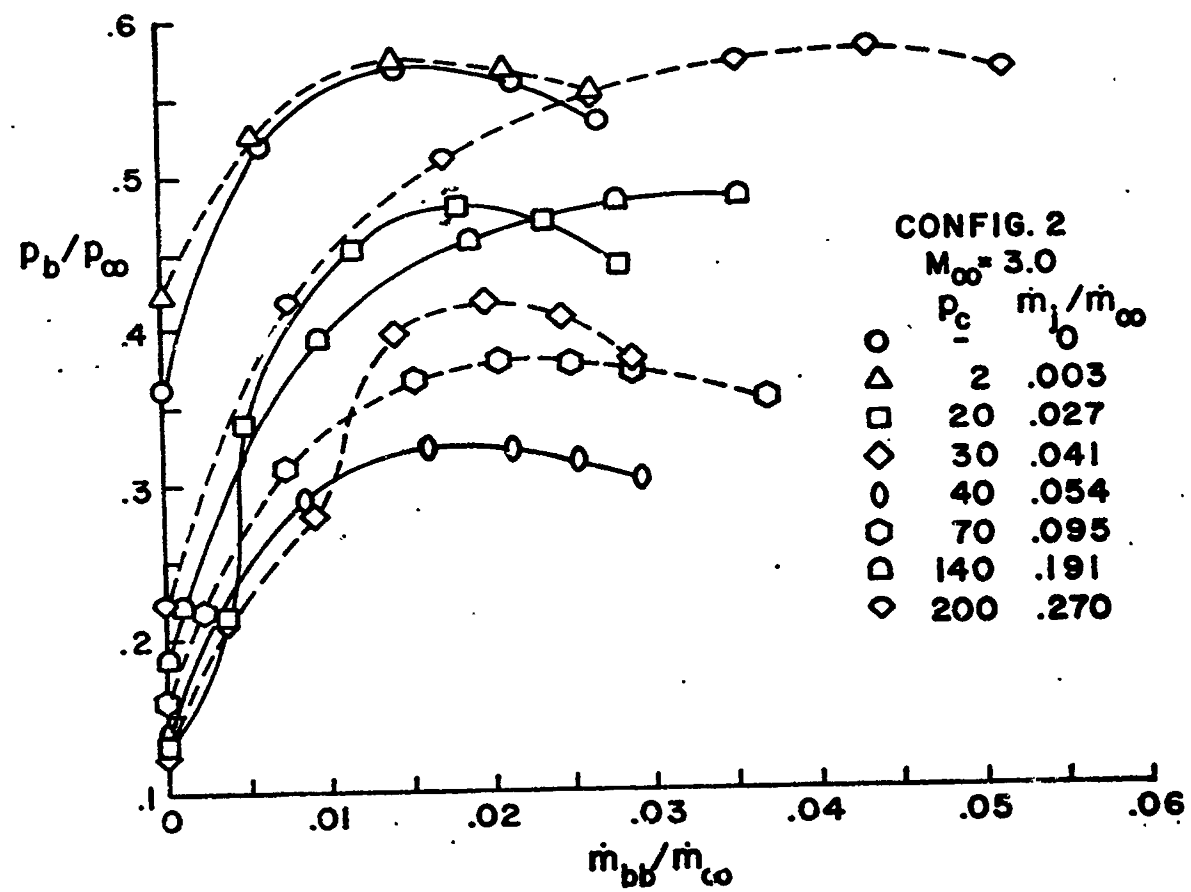

Figure 7. Continued

b. Configuration 2, M_∞ = 3.0

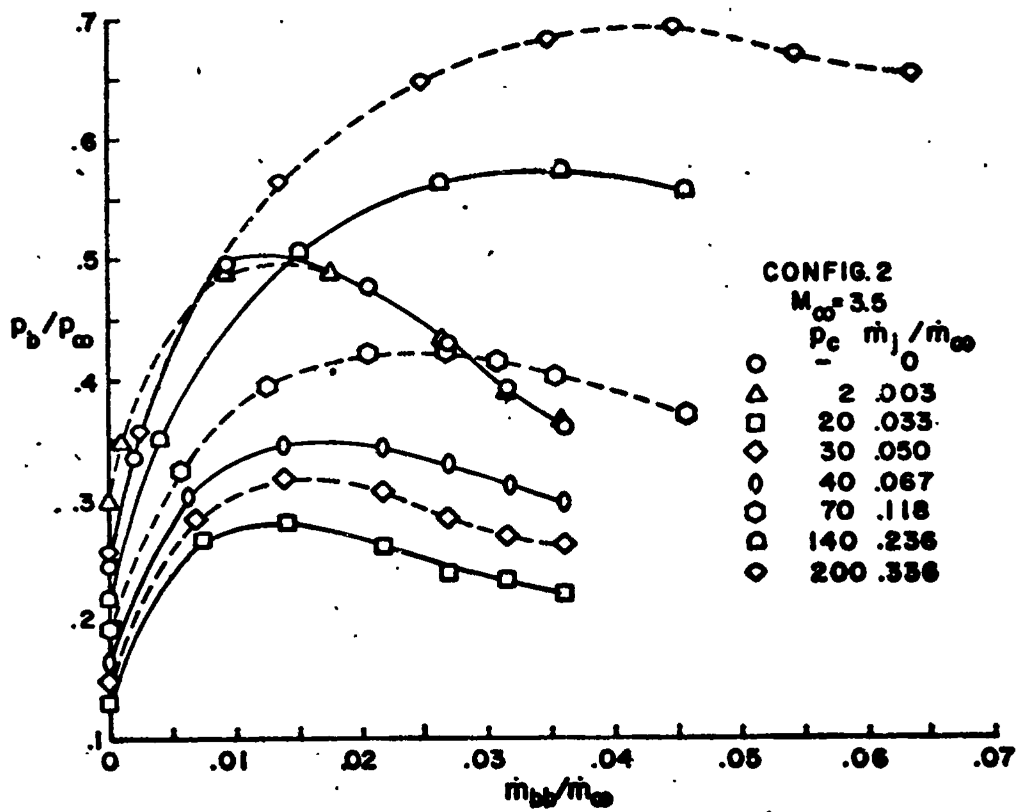

Figure 7. Continued

c. Configuration 2, M_∞ = 3.5

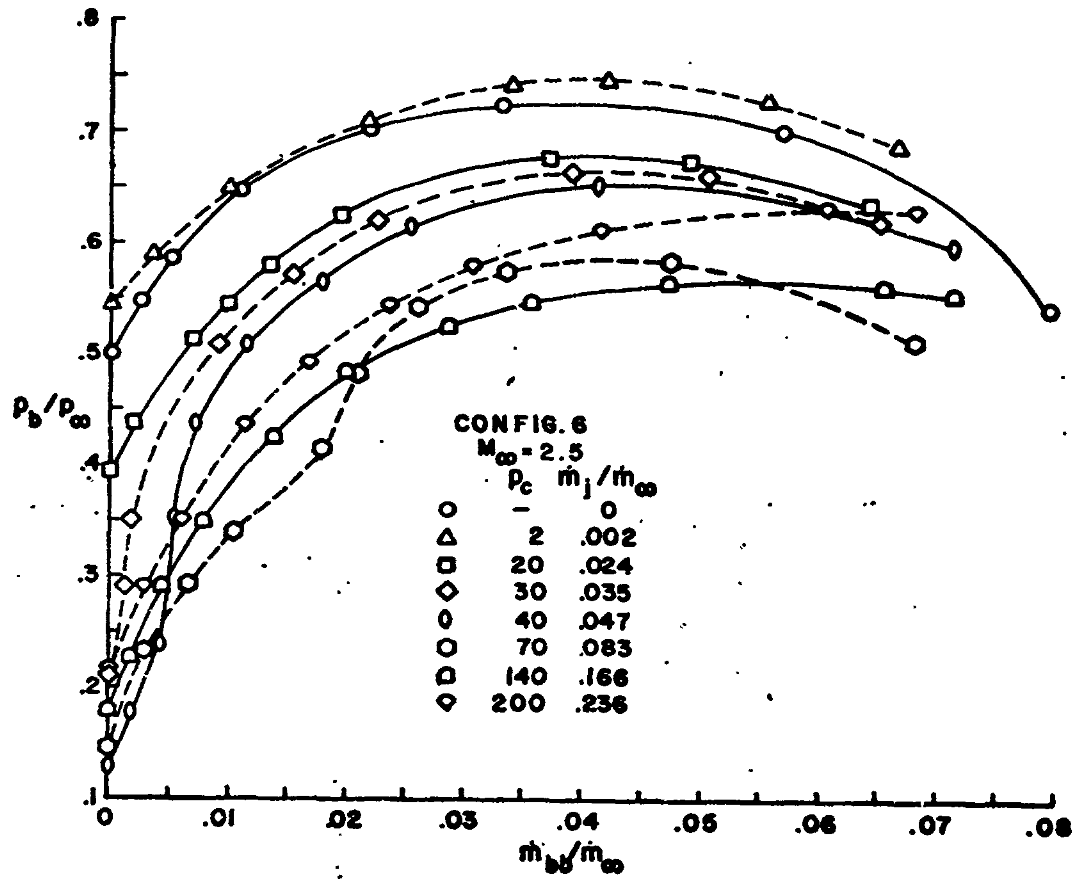

Figure 7. Continued

d. Configuration 6, M_∞ = 2.5

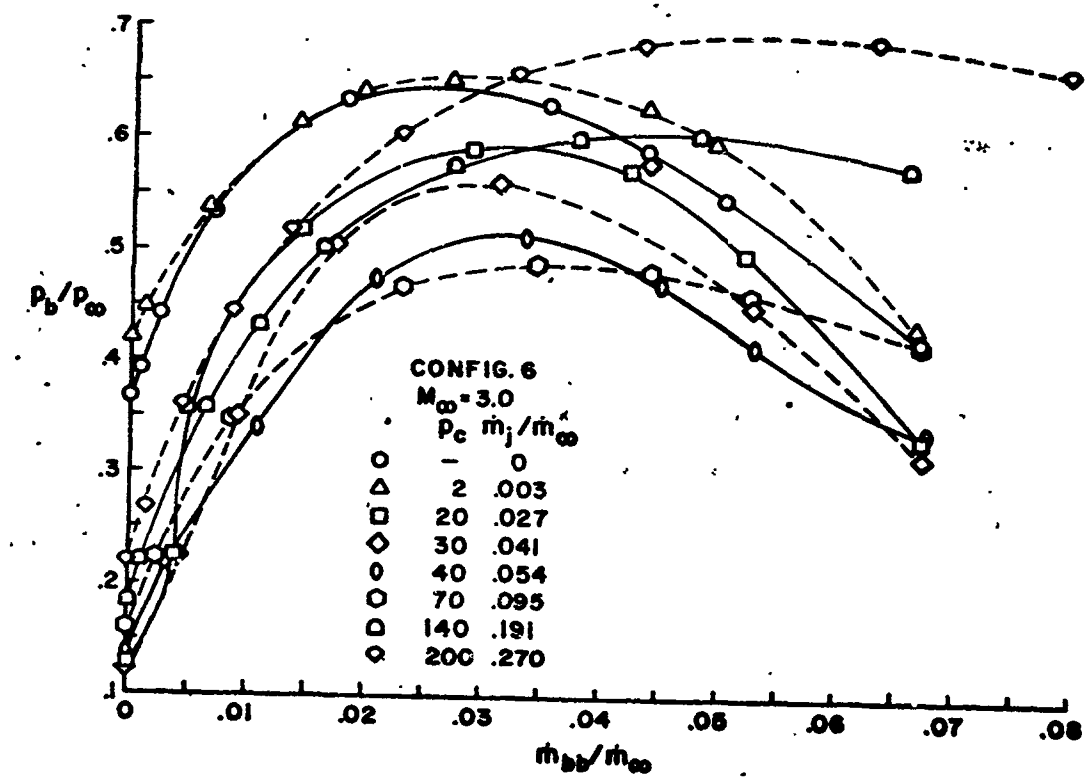

Figure 7. Continued

e. Configuration 6, M_∞ = 3.0

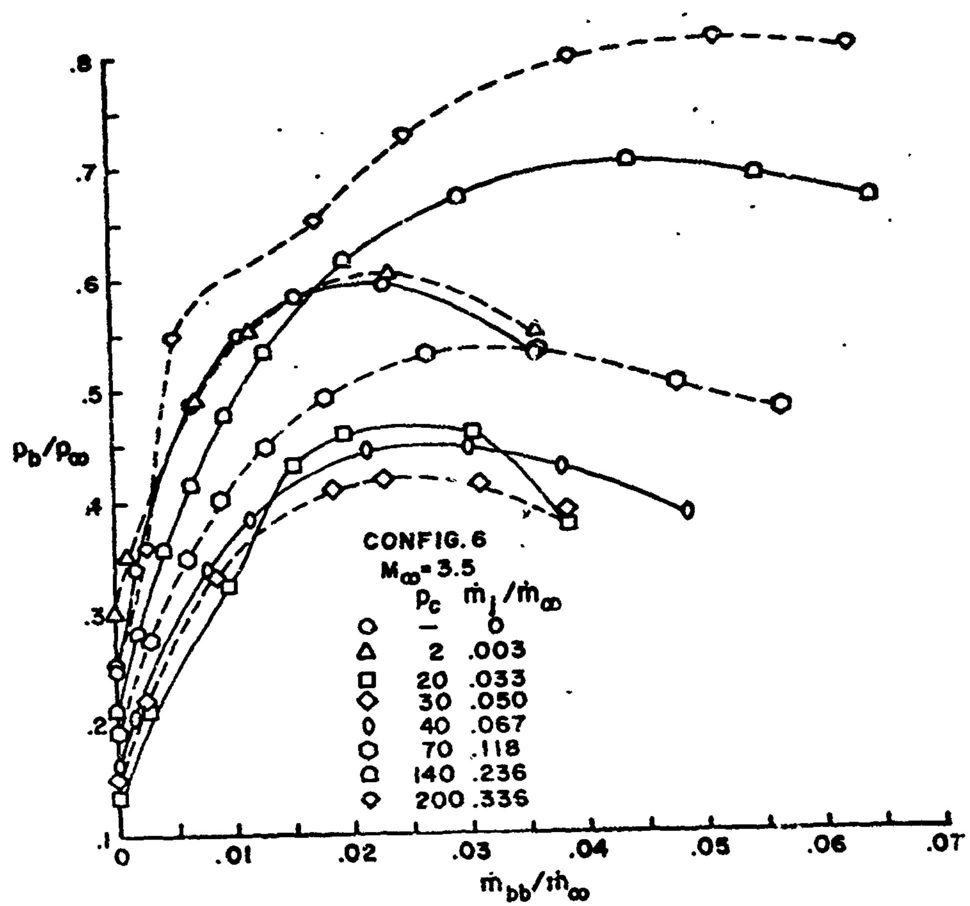

Figure 7. Concluded

f. Configuration 6, M_∞ = 3.5

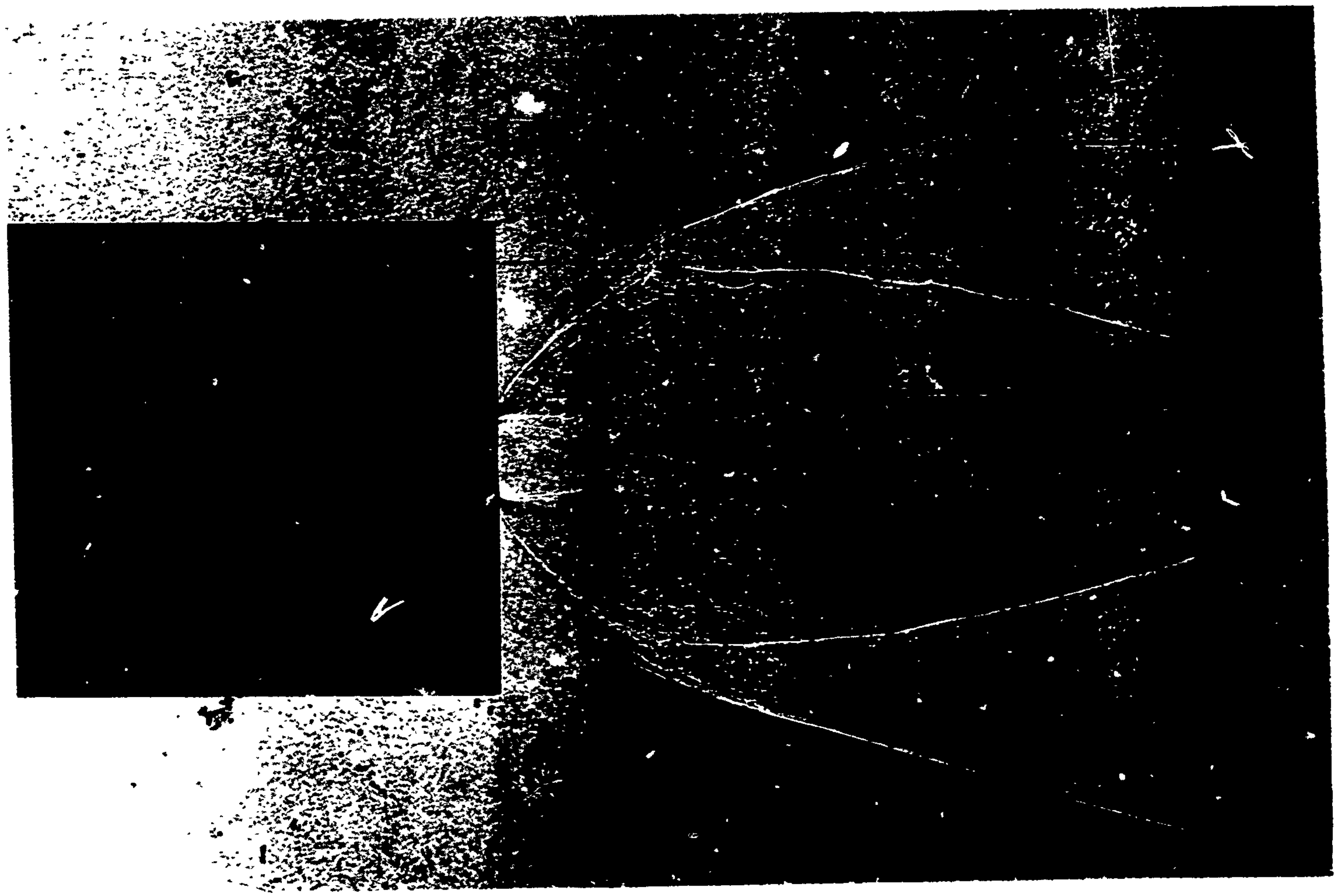

Figure 8. Shadowgraph

Configuration 6, $P_c = 200$, $\dot{m}_{bb} = 0$

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2. A. L. Addy, "Analysis of the Axisymmetric Base-Pressure and Base-Temperature Problem with Supersonic Interacting Freestream-Nozzle Flows Based on the Flow Model of Korst, et al., Part I: A Computer Program and Representative Results for Cylindrical Afterbodies," Report No. RD-TR-69-12, U. S. Army Missile Command, Redstone Arsenal, Alabama (July 1969). AD 861434.

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5. D. J. Collins, L. Lees and A. Roshko, "Near Wake of a Hypersonic Blunt Body with Mass Addition," *AIAA Journal*, Vol. 8, No. 5, May 1970, pp. 833-842.

LIST OF SYMBOLS

A	Model cross section area
$\dot{m}_{bb}$	Base bleed mass flow rate
$\dot{m}_j$	Supersonic nozzle mass flow rate
$\dot{m}_{B.L.}$	Boundary layer mass flow rate
$\dot{m}_\infty$	$\dfrac{\rho_\infty u_\infty A}{\mu_\infty}$
M_∞	Free-Stream Mach number
M_{air}	Molecular weight of air
M_i	Molecular weight of injectant
P_{bb}	Total pressure in base bleed chamber, psia
p_b	Base pressure
p_c	Supersonic nozzle total pressure, psia
p_∞	Tunnel free-stream static pressure
u_∞	Tunnel free-stream velocity
μ_∞	Tunnel free-stream viscosity
ρ_∞	Tunnel free-stream density

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